Virtual Haptic Validation for Service Manual Generation

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Abstract

We've designed and implemented a virtual validation system using haptics as well as other typical Virtual Reality equipment (head-mounted display, data-glove, and tracking hardware) for validating maintenance procedures and doing maintenance studies. The system uses a compact, sampled data representation to handle complicated geometric environments. Thus, the rate of collision detection is independent of the number of polygons in the source data. Also key to the system is an independent representation of the parts in the environment, allowing a random-access removal order. This allows a maintainer to validate a sequence of steps in a maintenance task, or instead to determine the sequence of steps defining the maintenance task. The validation system is part of a larger system (Service Manual Generation) to produce maintenance procedures in an automated fashion.

Introduction

Maintainability analysis involves analyzing the design of a system to ensure maintenance actions can be performed quickly, safely and accurately. Complex systems such as aircraft, power systems and appliances require timely, reliable and accurate documentation to support maintenance. As a result of such complexities, technical manuals with textual descriptions and exploded views of equipment describing, for example, how to remove, inspect, repair and install parts, are required to keep many complex systems in working order. The documentation is an integral part of the maintenance process. Thus, a thorough maintainability analysis should include the analysis of the product design and documentation working together. Unfortunately, maintenance manuals are typically one of the last items developed and delivered in a complex system [1,2].

To address this problem, a research effort was begun under contract with the Air Force Research Lab's Human Effectiveness Directorate [3] to investigate an automated approach to maintenance manual development. The three year program, entitled "Service Manual Generation" (SMG) [2,4,5], was started in 2001 and consists of three main components: Sequence Generation (SG), Task Generation (TG), and Virtual Validation (VV). The SG component is responsible for analyzing the CAD geometry of the relevant parts, producing an exploded view of the assembly, and determining a sequence of part removals for the purpose of maintaining a particular part, such as a "Line Removable Unit" (LRU) of an aircraft engine. The TG component takes the output of the SG component, and generates content for a maintenance manual authoring system, including the human-readable steps to perform the task, and Warnings, Notes, & Cautions associated with any of the steps. The final component, VV, has two main responsibilities. First, it enables the validation of the removal sequence produced by the SG component, to ensure that the sequence itself is feasible by performing the tasks after being given a visual depiction of the procedure. Second, it allows the user to verify the instructions produced by the TG component to ensure that the instructions adequately describe the task.

The VV component combines a number of virtual-reality technologies in an effort to provide a realistic environment for determining the validity of the steps within the sequence. These technologies include a stereo Helmet-Mounted Display (HMD) to immerse the user in the environment, a data-glove for modeling the hand in the removal process, a tracking system for mapping the real-world positions of the HMD and data glove to positions in the virtual environment, and a 6DOF SensAble ™ PHANToM™ for enabling realistic human interaction with the virtual environment (Figure 1). It is the use of haptics in this virtual environment that is the main topic of this paper.
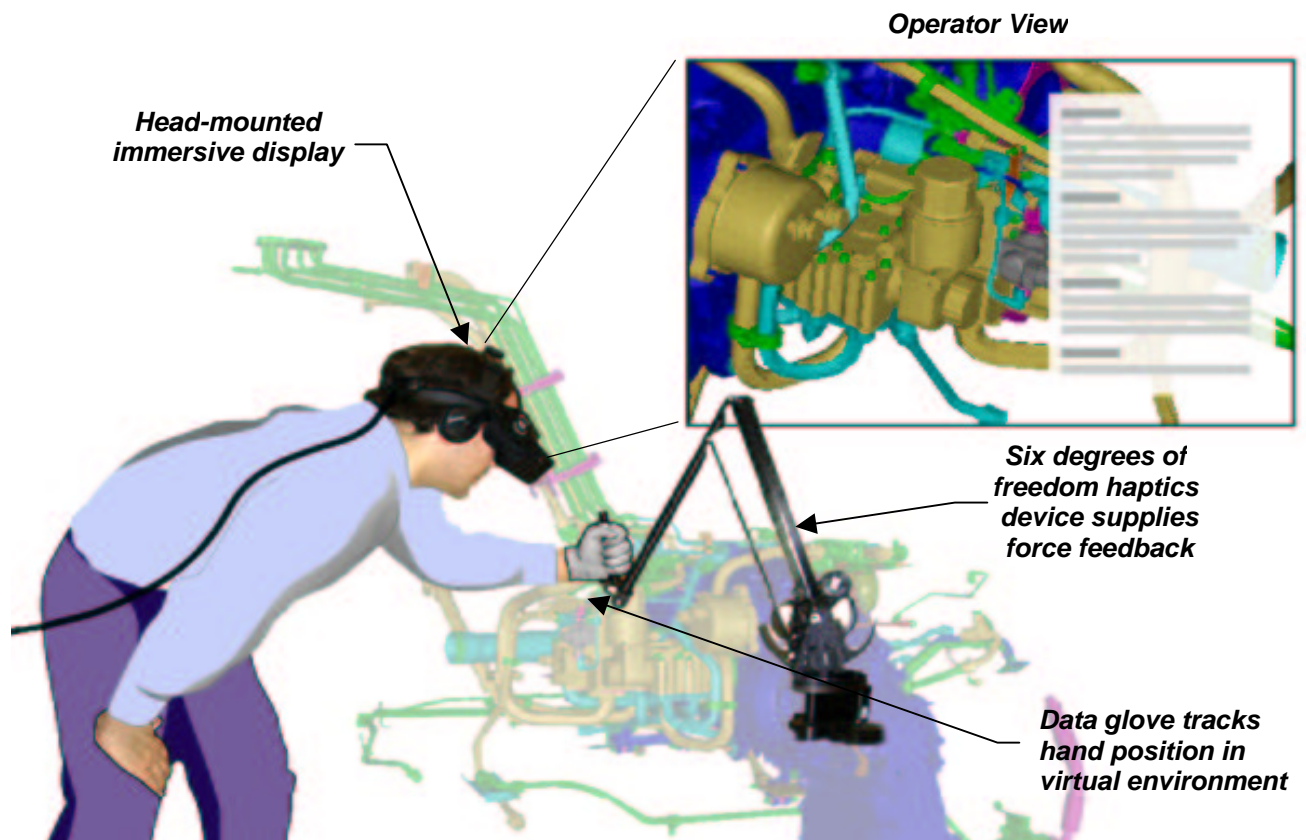
Operator View

Head-mounted immersive display

Six degrees of freedom haptics device supplies force feedback

Data glove tracks hand position in virtual environment

Figure 1: VV system

Haptics for Virtual Validation

GE Global Research has been working for some time on the use of haptics for maintainability analysis. Initial investigation for this task began in 1998, when we developed a collision technique based on using points sampled from the surface of a moving part, and a volumetric grid containing proximity/penetration information for the non-moving parts, similar to the technique developed around the same time by Boeing [6]. In the fall of 1999, we delivered a prototype Haptic Path Planner tool to the Joint Strike Fighter (JSF) military engine program at GE Aircraft Engines. This work provided the foundation for the haptic component of the Virtual Validation system in SMG. For Virtual Validation, we needed to enhance our approach to allow for parts to be selected in a random (user-determined) order as the moving part for removal. This allows multiple parts to be haptically removed in rapid succession. In the paragraphs below, we describe in some detail how we represent data in our haptic environment in a way that allows for multiple part removal, and how we perform fast collision detection, independent of the polygonal complexity of the models used in the environment.

Data Representation

There are three main components to our haptic representation. We describe each of these components in turn.

Surface Points. For each part that participates in the removal process, we generate a set of points that lie on the surface of the part which are evenly spaced and of sufficient density to adequately represent the part at a desired resolution. The surface points for a given part are used only when that part is the "moving part" in the environment.

Penetration Map. For each part relevant to the maintenance task, whether it is one to be removed or not, we generate a fine-resolution volumetric grid called the "penetration map", which contains proximity (penetration) information for points that lie outside (inside) the surface of the part, along with surface normals corresponding to the surface polygon nearest to the given point in the volumetric grid. In order to conserve space, this grid is arranged in a two level hierarchy in which a 4x4x4 block of grid points are grouped together to form a "brick". If all the grid points within a brick are greater than some maximum distance outside the part, or greater than some maximum distance inside the part, then the brick consists of a single value identifying that state. Otherwise, the brick is broken down into the 64 grid points with detailed penetration and surface normal information.

Part Map. The collection of (possibly overlapping) penetration maps of all the relevant parts defines a volume of space consisting of the union of all the volumes of the individual penetration maps. This combined volume is subdivided at a coarser resolution than the individual penetration maps to produce a grid called the "part map". This part map contains, at each grid location, a list of which parts are relevant within the space represented by the given part map grid location (Figure 2).
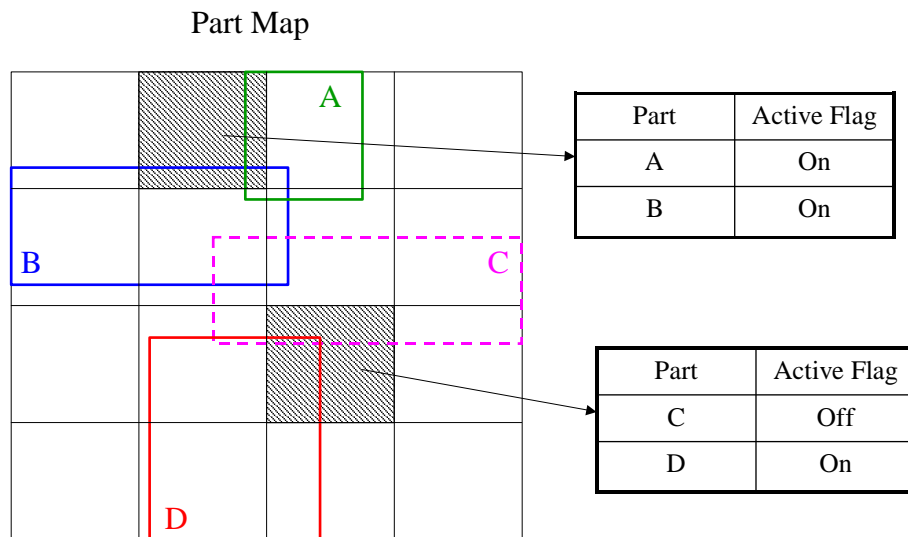
Part Map

Figure 2: Part Map example

Fast Collision Detection

At each iteration of the haptic collision detection process, the sampled points of the moving part are transformed according to the moving part's position and orientation in the virtual environment. The resulting location is indexed into the part map to determine which parts are possibly in contact with the given point. Since any one of these parts may have been previously removed in an earlier step of the removal sequence, each part has associated with it an "active" status flag, indicating whether or not it participates in collisions with the moving part (Figure 2).

For each active part in the part list at the current sampled point's location, we conduct a penetration test with that part's penetration map. Based on the sampled point's location, we look up the eight surrounding grid points in the penetration map and tri-linearly interpolate both the proximity/penetration distance and the associated surface normals. We keep track of whichever part the sampled point penetrates the most, and use that part's interpolated penetration distance and surface normal to calculate a collision response.

In order to take advantage of a sufficiently dense set of sampled points without wasting precious CPU cycles on points that have no chance of being in collision, we take advantage of the temporal coherence of the moving part through a technique called "skip counts". Each time a collision test is performed on a sampled point, we determine,

based on the distance of that point from the nearest surface and the maximum speed with which we allow a part to move, the minimum number of iterations that must pass before that point can possibly collide with any surface. This number becomes the "skip count" for the given point. At each iteration of the haptic loop, we decrement the skip count of each point for which the skip-count is non-zero, and perform the collision test only for those points whose skip-count is zero.

Current Research Issues and Future Tasks

In order to make our system more robust, we are currently investigating a variety of techniques for dealing with frequently occurring pathological situations in real-world data. One such situation occurs when the part has regions where the thickness is on the order of our sampling resolution. We frequently see this case in aircraft engine data for hollow tubes where the wall of the tube is thin. When this occurs, adjacent penetration map elements may reside on either side of the wall, resulting in the ability to pass through a wall without ever landing within the interior material, and thus failing to detect the penetration. The result is that the part can erroneously move through some regions of the penetration maps. We are currently evaluating several candidate solutions to this problem.

In order to accurately model the affects of the user's hand in the environment, we need to implement the ability to allow both a sampled point model of the data glove and the moving part to participate in the collision response simultaneously. The colliding hand points will affect the haptic collision response in the same manner as the sampled points on the moving part. Furthermore, we can scale the hand model to perform human factor analyses of a task.

A similar needed interaction within a maintenance environment is that of tools, which must fit snugly over certain parts without being repelled, and which must be kinematically constrained to move with fewer degrees of freedom. This ensures that not only can a part be removed, but also that it can be removed using the tool designated for the task.

References

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